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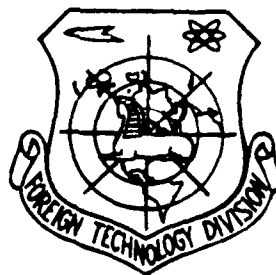
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THE CHARACTERISTICS OF PHYSIOLOGICAL RESPONSES AND TOLERANCE EVALUATION
OF PRESSURE BREATHING

by

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The Characteristics of Physiological Responses and Tolerance Evaluation of Pressure Breathing

Chen Jingshan, Zhang Baolan and Jia Siguang

Experiments were performed on 6 young healthy males during pressure breathing without trunk counter-pressure. The values of intra-pulmonary pressure used were 0, 2.0, 3.0, 3.4, 4.0, 4.4 and 5.4 kPa. The results were summarized as follows.

With the increase of pressure within the lung, the compensatory functions of circulatory and respiratory power consumption index was increased, but it was dropped as the intra-pulmonary pressure reached 4.0 kPa. The decrease of above objective physiological indices showed that the compensatory function was weakened, weakened, which was the indication of physiological endurance limit during pressure breathing. There was a serious subjective symptom for the breathing to be continued difficulty experimental examples discontinued only, that may be considered as the acceptable endurance index.

The respiratory power consumption index can reflect respirodynamically physiological characteristics of subjective sensation in human during pressure breathing which may be used as a co-indicator for the evaluation of tolerance. A method of comprehensive evaluation of the tolerance of pressure breathing was presented through the experiment. The intra-pulmonary pressure of 2.0, 3.4, and from 4.0 to 6.2 kPa was considered to be the physiological limit of safety, allowance and endurance. This study denoted marked significance for establishing physiological standard and protective measure of pressure breathing by oxygen.

Key words: pressure breathing, physiological limit, intra-pulmonary pressure, *pressure breathing, physiological limit, intra-pulmonary pressure*

The physiological effects of positive pressure breathing are important in the formulation of standards of pressure oxygen supply standards and in fundamental research into protective (equipment and protective measures). In the wake of the rapidly developing needs of aviation, a great deal of testing and research progressed from the 1940's through the 1960's which revealed that simple positive pressure breathing caused subjective symptoms: principally it had an effect on the circulation function and this serious level of organism reaction was evaluated according to positive pressure breathing endurance [1-6]. These works are principally limited to qualitative analysis and evaluation, although formulations are incomplete, to make clear various physiological limits, even so far as to

treat wide-ranging applications such as endurance and allowable limits [5,6]. Obviously there has already been a great deal accomplished in this field and much remains to be done to deepen and enhance knowledge in this area. In this study we will attempt to by methods of composite analysis nad quantitative evaluation of physiology and respirodynamics to gain a comprehensive clarification of the physiological effects of simple positive pressure breathing, establish evaluation methods for positive pressure breathing endurance and define each physiological value, remedy deficits in this field and therefore formulate a scientific basis for the establishment of standards and protective measures.

I. Methods

The subjects were 6 healthy young males. Natural breathing was carried out under normal room temperature and a KII-T pressurized oxygen-supply training device (supplies pure oxygen) and a self-controlled respiratory impedance measuring device forming the positive pressure breathing system. The experiment was divided into training, measurement and comparison. Each person in the training group respectively underwent respiration 3 to 4 times using different pressures of 2.0, 3.4, and 4.4 kPa. In the measurement group each subject underwent continuous breathing for 5 to 6 minutes at 7 pressures: 2.0, 2.9, 3.4, 4.0, 4.4 and 5.4. Each time 2 to 3 pressure values were used for a total of 4 times. The control group underwent continuous respiration for 15 min. with each subject receiving 3.4 or 4.0 kPa and the emphasis of this paper is on endurance of physiological effects of the two pressures and endurance.

The measured indices of the experiments were : respiration rate (f), tidal volume (V_T), pulmonary ventilation volume , systolic pressure, diastolic pressure, pulse rate, average arterial pressure, heart rate, electrocardiogram, respiration system dynamic confirmation (C) and the respiratory power consumption index (M_c).

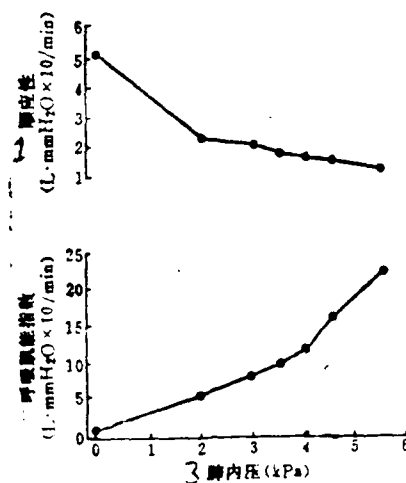
Among these, the respiration system dynamic compliance uses the forced oscillatory method of respiratory impedance for determinations [7]. The respiratory power consumption index can be calculated by the following:

$$M_c = \frac{V_T^2 f}{C}$$



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Fig. 1 Changes in the respirodynamic parameters during pressure breathing at different pressures. The curves within the fig. are averages of 6 subjects. Key: (1). Compliance, (2). Respiratory power consumption index, (3). Intrapulmonary pressure (kPa)



11. Results and Analysis

1. Physiological Reactions to Positive Pressure Breathing

(1) Changes in Respirodynamic Parameters (fig. 1)

The dynamic compliance of the respiratory system follows increases and decreases of intra-pulmonary pressure and this clearly indicates that thoracic elasticity tissue changes. During the respiration process the changes of each unit volume of the lungs are reflected by increases in the respiratory muscle strength. During respiration at 2.0 kPa, the decreasing rate of dynamic compliance slows down and this can be explained by an increase in lung relaxation pressure: at this time the respiratory muscles are not yet completely relaxed and this indicates that this is the main reason why respiration causes the respiratory muscles to be burdened. The increases in the respiratory power indices indicates that during positive pressure breathing in a set length of time, the respiratory muscles surmount thoracic elastic tissue resistance to make an effective increase and gradually consumption becomes regular.

The respiratory power consumption index rises when the intra-pulmonary pressure is increased and it is clear that during positive pressure breathing within a certain length of time that the respiratory muscles are used to surmount the thoracic elastic tissue resistance which increases and this causes compliance to drop and the subjective sensation of respiration gradually appeared to be strenuous and regular. This can be explained by the fact that the respiratory power consumption index is regarded as one of the dynamic characterizing indices of the sensation of positive pressure breathing and it has a special physiological significance. The rate of increase at approximately 4.0 kPa began to quicken after 3.4 and 4.0 kPa the control experiment was verified: at 3.4 kPa the respiratory process, the sensation of respiratory fatigue was not noticeable; at 4.0 kPa, the sensation of respiratory fatigue was obvious. When a positive pressure of 4.0 kPa was continued for 8 to 10 min., the subjects began to perspire and some had difficulty breathing which required the experiment to be discontinued. These were clear characteristics of the endurance limit of positive pressure breathing. Therefore, it is clear that the beginning of the acceleration of the respiration power consumption index is significant because it can be used to judge the beginning of the limits of endurance of short-term positive pressure breathing.

F. Being aware of the serious symptoms, it was difficult to maintain through completion the respiratory movement in the test cases (tables 1,2). and among the subjects who received the same intra-pulmonary pressure process, those subjects who stopped during the test had larger respiratory power consumption indices than those who completed the test. Furthermore, those who had different intra-pulmonary pressures during respiration had relatively similar respiration power consumption indices when testing was discontinued; it is clear that the greatest respiratory power consumption indices were of subjects who had difficulty bearing the respiratory process during positive pressure breathing. Therefore, this value is a significant parameter in judging the maximum limit of endurance of positive pressure breathing to complete respiratory movement with difficulty. The values can be calculated according to the regression equation (fig. 2). The maximum short-term endurance limits of positive pressure breathing of 4 subjects were: Cui XX was 5.8 kPa, Nan XX was 6.8 kPa, ZhangxueX was 5.9 kPa, and Zhang was 6.3 kPa. The average was 6.2 kPa. Changes in each index are clearly shown in table 1 by comparison of the cases which completed the experiment and those which were discontinued. The respiratory power consumption index had clear, regular changes

Table 1 Physiological indices of discontinued and completed experimental cases during pressure breathing in 4 subjects

1 实验例	M_c	C	R	V_T	f	\dot{V}_E	P	P_s	P_d	P_{s-d}	HR
2 崔XX	5 肺内压4kPa										
3 中止	20.7	1.1	4.0	1196	12.3	14.7	86	119	69	50	85
4 完成	7.1	2.2	3.8	1072	13.6	14.6	100	118	90	28	73
	8.6	2.1	3.7	1234	12.9	15.9	105	131	92	39	85
	9.3	1.3	5.8	1648	10.7	11.2	103	130	90	40	70
10 张学X	6 肺内压5.4kPa										
3 中止	54.3	0.4	4.5	1334	12.2	16.3	96	119	84	35	73
	53.3	0.4	4.8	1252	13.6	17.0	104	128	91	37	78
4 完成	36.2	0.5	4.6	1057	16.2	17.1	101	135	84	51	72
南XX	7 肺内压5.4kPa										
2 中止	39.9	0.6	4.1	1321	13.9	18.4	104	152	81	71	74
4 完成	22.4	1.1	3.9	1327	15.9	21.0	101	134	84	50	83
	24.5	0.9	3.0	1305	15.7	20.5	103	136	87	49	84
	16.5	1.0	3.3	1215	10.4	12.6	108	142	90	52	53
9 张XX	8 肺内压5.4kPa										
3 中止	17.1	1.8	1.4	1302	18.4	19.5	106	144	88	58	92
4 完成	14.5	1.6	1.0	1414	9.6	13.6	107	136	92	44	77
	14.4	1.8	1.1	998	12.3	12.3	107	130	96	34	79
	10.4	2.1	0.9	1187	5.5	6.5	98	135	80	55	74

Note: M_c -Respiratory power consumption index, C - compliance, R - Human respiratory system tissue resistance, V_T - Tidal volume, f - Respiratory frequency, \dot{V}_E Volume of ventilation, P - average arterial pressure, P_d diastolic pressure, P_s systolic pressure, P_{s-d} pulse pressure, HR - heart rate, All of the indices units are the same as fig. 1.

Key: (1). Case (2). CuiXX (3). discontinue (4). Completion (5). Intrapulmonary pressure 4kPa (6) Intrapulmonary pressure 5.4 kPa (7) Intrapulmonary pressure 5.4 kPa, (8) . Intrapulmonary pressure 5.4 kPa (9). Zhang XX (10) Zhangxue X

Table 2 Changes in the respiratory power consumption index for the completed experiment (15 continuous minutes) and the discontinued experiment (9 continuous minutes) with pressure of 4 kPa in subject 1 (Zhangxue X)

Key (1). Time (min) (2). Experiment (3). discontinued experiment (4) Completed experiment

1 时间(min)	实 验	
	3中止实验例	4完成实验例
1	25.7	18.2
2	30.0	16.2
3	32.7	24.8
4	33.0	27.7
5	28.5	47.0
6	45.5	21.5
7	30.0	15.2
8	57.0	25.2
9	50.8	24.5
10		27.3
11		32.8
12		29.0
13		32.1
14		35.1
15		47.6

Fig. 2 Changes in the respiratory power consumption index in 4 subjects using different intrapulmonary pressures

Key (1). Zhang XX (2). CuiXX (3) Zhangxue X (4) Nan XX (5). Respiratory Power Consumption Index (6). Intrapulmonary pressure (7). Limiting value (8). Average value of 4 subjects

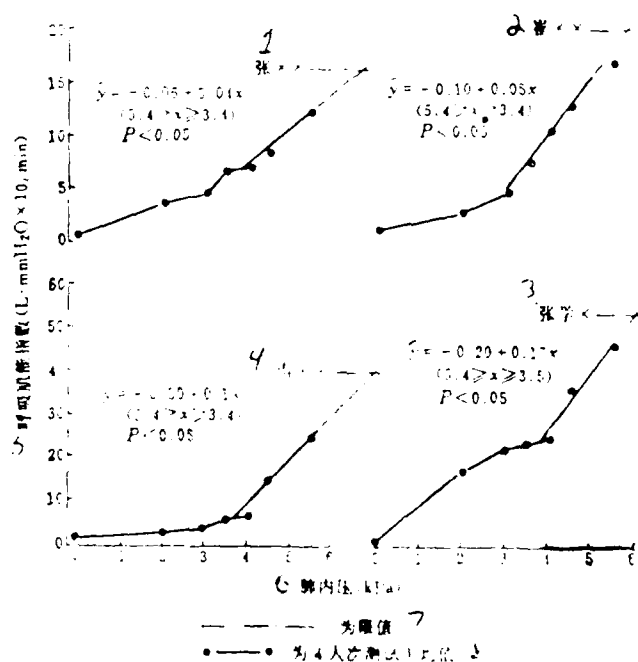
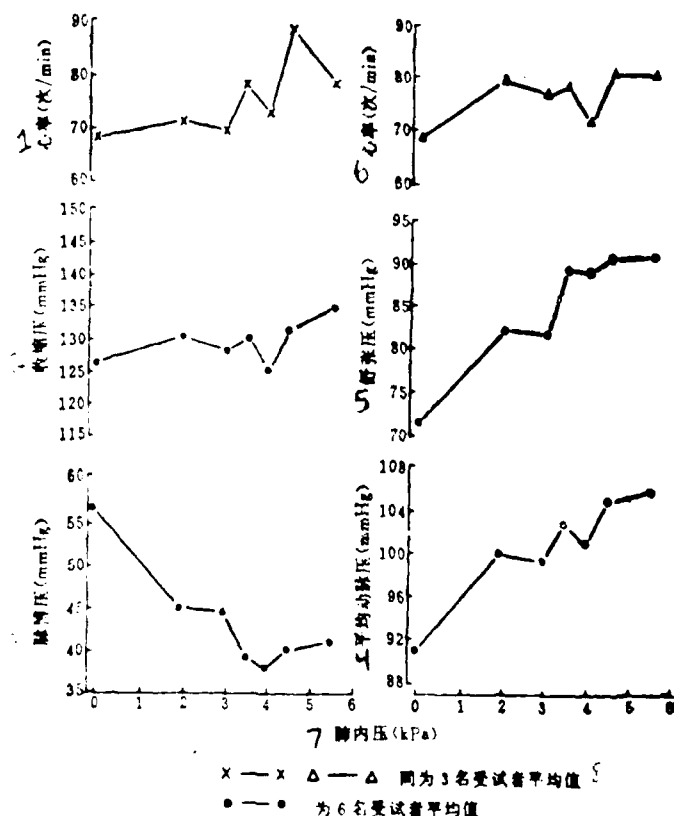


Fig. 3 Changes in the circulation and the respiration indices at different intrapulmonary pressures

Key (1).Heart rate (beats/min) (2). systolic pressure (3). arterial pulse pressure (4). average pul pressure (5). diastolic pressure (6). Heart rate (beats/min)



only in the group which discontinued the test. These results indicate that the respiratory power consumption index is a sensitive standard in evaluating the endurance limits of positive pressure breathing.

(2) Changes in the Circulation function (fig. 3)

The intrapulmonary pressure was between 2.0 and 3.4 kPa during respiration and was compared to control values. Systolic pressure increased slightly. There was a clear increase in average arterial pressure and diastolic pressure ($P < 0.001$), there was a significant decrease in pulse pressure ($P < 0.001$). Changes in the heart rate were individual: in three individuals there were no changes and

in three individuals there were clear increases. Overall, the circulatory function was in a good compensatory state. Only at the intrapulmonary levels of 4.9 kPa did systolic pressure decrease to pre-pressure levels and at 3.4 kPa there were comparatively significant differences ($P < 0.05$). Diastolic pressure rose to a high level, pulse pressure decreased slightly and average arterial pressure significantly decreased at 3.4 kPa. The heart rate decreased significantly and approached control levels. These results indicated the abnormal phenomenon of a small compensation of circulation function. When the intrapulmonary pressure is higher than 4.0 kPa, the diastolic rate remained steady at high levels, systolic pressure, average arterial pressure increased significantly. pulse pressure which was at low levels again increased and the heart rate clearly increased.

(3) Changes in REspiration Function (fig. 4)

Volume of ventilation increased dramatically during respiration when intrapulmonary pressure was in the range of 2.0 and 4.0 kPa and the increase in pulmonary ventilation effect was principally dependant on increases in adjustment of the depth of respiration. When intrapulmonary pressure was 4.0 kPa, the ventilation effect increase lessened. This was due to the decrease of the rate of increase of the depth of respiration and the apparent increase in the volume of ventilation was principally due to an increase in the respiratory rate.

When intrapulmonary pressure was 4.9 kPa, the increase rate of volume of ventilation decreased. Inherent ventilation effect was 4.0 kPa. It approached an increase in adjustment of volume of ventilation. These findings indicate when the value of intrapulmonary pressure is high, respiratory function

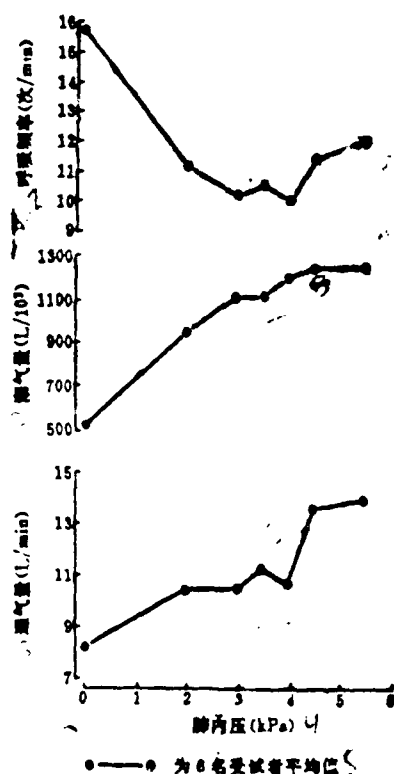
2. Evaluation of Positive Pressure Breathing

The above composite analyses are principally objective observation indices which clarify each endurance limit. Systematic evaluation was performed of experimental results of measurements under conditions of different pressures to obtain the limiting values (8).

(1) Limit of Safety

The respiratory and circulation functions of the subjects are enhanced when the intra-pulmonary pressure is 2.0 kPa, the falling rate of respirodynamic compliance slows, respiration takes on a completely abnormal form, the respiratory power consumption index is distant from the value of the endurance limit and respiration sensation is somewhat symptomatic under this value, positive pressure breathing causes clear changes in the function of the human body, and this limit of safety is suitable in evaluating positive pressure breathing during relative

Fig. 4 Changes in the respiration parameters at different intrapulmonary pressures
Key (1). Respiration rate (2). Tidal volume (3). Ventilation volume
(4) Intrapulmonary pressure (5) Average value for 6 subjects



long-term positive pressure breathing in the upper atmosphere and establishing standards for safety and protective equipment for supplying oxygen.

(2) Limit of Allowance

When intra-pulmonary pressure was 3.4 kPa, respiratory and circulatory function were in a good compensatory state, the respiration power consumption index increased to a medium level, and when the experiment was discontinued after 15 minutes, there was no obvious respiratory fatigue, although the respiration was somewhat adversely affected, although there was good endurance of short-term respiration. It is believed that this value is the limit of allowance for 15 minutes of positive pressure breathing and is the highest value which should be selected for pressurized oxygen supply equipment.

(3) Limit of Endurance

When the intra-pulmonary pressure was 4.0 kPa, there was a slight compensation of circulation and two of the subjects in the study experienced subjective symptoms such as dizziness and nervousness and the rate of increase of the respiratory power consumption index accelerated. ^{Result of 15 min test indicated that} After 8 to 10 minutes of continuous breathing the sensation of respiration became heavier and this value was suitable as the short-term positive pressure breathing limit of endurance. The maximum respiratory power consumption index for the subjects was calculated and the maximum limit of endurance which could be tolerated was an average of 6.2 kPa.

4. Discussion

Through various observed indices of objective reactions, we have shown the regular changes in respirodynamics, subjective reaction and in respiratory and circulatory functions under different pressures. It was shown that with increases in pressure values, there was a trend of a gradual enhancement of compensation of respiratory function and when the level of the limit of endurance was reached, when 4.0 kPa was used, the compensatory function was insufficient. When the pressure was increased, the various parameters of respirodynamics exhibited regular and characteristic changes in the thoracic muscles and pulmonary tissue. However, the standards of subjective sensation also indicated reactions of

significance and this data from comprehensive analysis verifies that using different pressures, that both the circulatory and central nervous systems are regulated by different reactions. By understanding these regular reactions we further deepen our understanding of the physiological effects of positive pressure breathing and from this we can establish methods of determination and the physiological limits. This type of comprehensive data on the physiological effects of different pressures in the same body for the same time are published here for the first time.

Generally, endurance limit of positive pressure breathing can be determined by perception of respiration and by the critical level of circulatory function (5,6,9) and the dizziness and fainting have also been used as a standard of the limit of endurance (4). In this paper we have made clear through the results of composite analysis that when the level of the limit of endurance is achieved (Pressure value becomes 4.0 kPa), the first abnormal objective standard to appear is a slight insufficiency of respiratory circulation compensation: at this time if subjective symptoms worsen, then the subjects present difficulties and the experiment was discontinued. When the subjective symptoms did not appear, even if pressure is raised to 5.4 kPa, then respiratory circulation function continues to increase. The cases when the experiment is discontinued were due to subjective symptoms such as difficulty in breathing. The verification of this data - an insufficiency in the respiratory circulation compensation - is also an advance expression of the limit of endurance and this is a standard which sufficiently reflects the critical level of the subjective reaction.

It is clear from this work that the sensitivity of the respiratory power consumption indices reflect the dynamic effects of positive pressure breathing on the human respiratory muscles and that a determination of the limits of respiratory endurance can be made using these values. It can be seen by equation (square method) that these physiologically significant values can make effective scalar quantities which show that thoracic elastic tissue resistance in respiratory muscles during the respiratory process can be overcome within a certain time and a certain unit. These values reflect the inherent relative partial load intensity of respiratory muscles during the respiratory process. This load intensity can determine the respiratory fatigue time and the surmountable respiratory resistance of the respiratory muscles during the respiratory process.

The published limits of endurance for positive pressure breathing vary and some authors (5,6,9) give endurance limits of 3.3, 4.0 or 3.3 to 3.4 kPa for

short-term positive pressure breathing (10 to 15 min) In this study all of the objective indices equally show that a value of 4.0 kPa is the value which causes a decrease in the objective physiological indices and when subjective reactions were severe, the experiment was discontinued. When a pressure of 3.4 kPa was used, all of the above-mentioned objective indices exhibited a continual increase, the subjective reactions were not serious.

IV. Conclusion

Under seven different pressure values between 0 and 5.4 kPa, respiratory and circulatory function gradually intensified, compliance gradually decreased, the respiratory power consumption index gradually increased and at a pressure of 4.0 kPa all of these indices decrease. When subjective reactions reach the level of the endurance limits, the experiments were discontinued.

A decrease in respiratory circulation function appeared to be a precursor to compensation insufficiency or the limit of endurance. The seriousness of the subjective reactions can be used as a standard to evaluate the limit of endurance, to calculate the respiratory power consumption index which reflects the dynamic characteristics of respiration sensation under different pressure values and can be used to evaluate protective standards for the limit of endurance.

In this study we offered a method for the comprehensive evaluation of the tolerance of pressure breathing and established three types of physiological limits: limit of safety, limit of allowance and the limit of endurance. These limits are significant in the establishment of physiological standards and protective measures of pressure breathing with oxygen in aviation.

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